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Space Saver Bike Rack

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Senior Project

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By

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Abstract: Space Saver Bike Rack
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Apartment living can be crowded especially for a cyclist. Bicycles are bulky and difficult to store. A device is needed to store two road bikes weighing up to 40 pounds each while saving as much space as possible. To solve this problem many iterations of various free standing and wall-leaning bike rack designs were drawn. Evolution of the design can be traced through the drawings included in the report. The first design analyzed was a free standing rack. After calculations and adjustments this design was going to have to be very bulky in order to achieve the stability requirements. The next design that was analyzed was a wall-leaning rack. This design was very compact and satisfied the stability requirements gracefully. In winter, materials were ordered and prepared for construction. Construction included cutting ABS pipe, gluing or drilling and pinning fittings. Construction was completed without major issues. The final device is working properly despite a couple of minor clearance related oversights. The bike rack supports two bikes weighing 35 pounds each. The compactness requirement of 72 inches squared was met. This spring the deflection of the rack will be tested and compared to the predicted data. The racks capacity to support loads up to 40 pounds will be tested. A test will be run where the rack is loaded with two bikes and the floor area and volume occupied can be found. These values will be compared to the original configuration of road bike leaning against the wall in the apartment.

Table of Contents:

INTRODUCTION

Why Build a Bike Rack/Engineering Merit

Bicycles are a highly efficient and economical form of transportation. Having convenient access to your bicycles can often clutter a hallway or entry room. Presently, two bikes take up about 52ft^3 in a hallway and 18ft^2 of floor area. A device is needed that will store two road bikes while saving as much space as possible.

Many commuting cyclists are trying to save money but the current options for bike racks cost an average of $150. A rack is to be designed that is less expensive than the competition. To reduce the price, the rack will come in a kit that is to be assembled by the end user. Also, the rack will be made of affordable ABS plastic pipe. This project will focus on making a rack that is simple to assemble and that will fit in a UPS shipping box. This plan will focus on the construction of a wall leaning bike rack from start to finish.

The engineering merit of this project is what drew me to it. The rack had to be drafted numerous times before a sufficient design was created. The problem of creating a rack that was both very stable and easy to assemble took some consideration to solve. See appendix B for preliminary design sketches. Another source of merit is the reduction in cost of the bike rack in comparison to current options. Engineers are always being asked to make project cost effective and that virtue is to be applied to this project. This assignment will require careful analysis to be a success. The material will have to be rigid enough not to deflect under the load of the bikes. The stability of the bike rack is key to its success for it must not tip under load. First the static analysis of the rack must be analyzed and optimized. Then the rack must pass a tipping test to truly be called stable and an overload test to be deemed safe. The problem calls for the optimization of cost, stability and rigidity. The failure mode of critical stress on the mounts is to be analyzed.

Functions

A device is needed to perform the following functions:

- To support the load of two road bikes.
- To be stable and free standing.
- To allow easy access to both bikes.
- To be easily assembled.
- Able to be shipped in a standard UPS box.

Requirements

A device is needed that can fulfill the following requirements:

- Must be no larger than 16” wide and 84” tall and 19” deep (+/- 0.5”).
- With bikes mounted, the device must conform to a volume of no more than 67” wide 19” deep 84” tall (V = 52 ft^3 (+/- 4 ft^3)).
- Must meet a safety factor of 2.0
- Must occupy no more than 10ft^2 (+/- 0.5 ft^2) of floor area.

- Must support two instances of: a 40lb load, placed on two horizontal supports. This load is placed at 42” high and again at 84” high (+/- 0.5”). The load points down, perpendicular to the support members.
- Material scrap rate of 80%
- Must not deflect more than 0.25” (+/- .05”) at the vertical member, under bike load.
- Must resist a moment of 65 lb-in at the base.
- Must resist s horizontal tipping load of 14lb at the top in the forward, backward and side directions.
- Must withstand an impulse of 40lb at both mounting points without tipping.
- Must support 2 bikes.
- Must be safe to operate (no danger of tipping during use).
- Must be free standing.
- Must be metallic or black.
- Must weigh less than 40lb.
- Must be able to assemble alone without tools.
- Must cost $50 or less in parts.
- Must fit in a shipping box of 165in of length and girth combined with L<108in.

Success Criteria

The bike rack will be considered a success if it can fulfill the following success criteria:

- Safe to operate.
- Holds two bikes.
- Inexpensive to produce (around$50)
- Takes up 52ft^3 or less with bikes mounted.
- Easy to assemble without tools in a reasonable amount of time.
- Stabile under vertical bike loads and horizontal tipping loads.
- Aesthetically pleasing.
- Fits into a UPS allowable box size.
- Capable of sequence: 1) unpacking and assembly 2) bike loading and unloading 3) Disassembly and repacking.

DESIGN

Approach

To get an idea of what kind of rack dimensions were going to be needed the bike had to be measured first. See figure 1 for an example of the kind of bike dimensions the device must fit. The plan is to have the bikes hang by the top tube (20.5in) with hooks in two places. The height of the bike doubled has driven the height dimension of the bike rack. The depth must also be greater than 17.5in so that the bikes do not rub against the wall. The construction material will be ABS plastic and the geometry will be simple. This will streamline the analysis as well as the assembly for the end user. The rack will have to be rigid enough to hold the weight of two 20lb bikes.

Figure 1: Bike Dimensions

Description and Sketch

The concept of the device changed many times in an effort to optimize ease of assembly, stability and space saving. Early designs kept running into issues with the requirements. Some of the sketches were going to be too complex to assemble and others didn't have the desired stability. Numerous design ideas had specialized parts that would increase the cost too much. The final design was selected because it was the simplest design for the end user to assemble. The simplicity of assembly was optimized to appeal to the DIY consumer and make the "kit" shippable. The design went from a single load bearing member to a double load bearing member in an effort to increase stability. These criteria were considered in the final design while saving as much space as prior designs by not exceeding the 52ft^3 requirement. A virtual representation of the rack has been drafted in Solidworks, see figure 3.

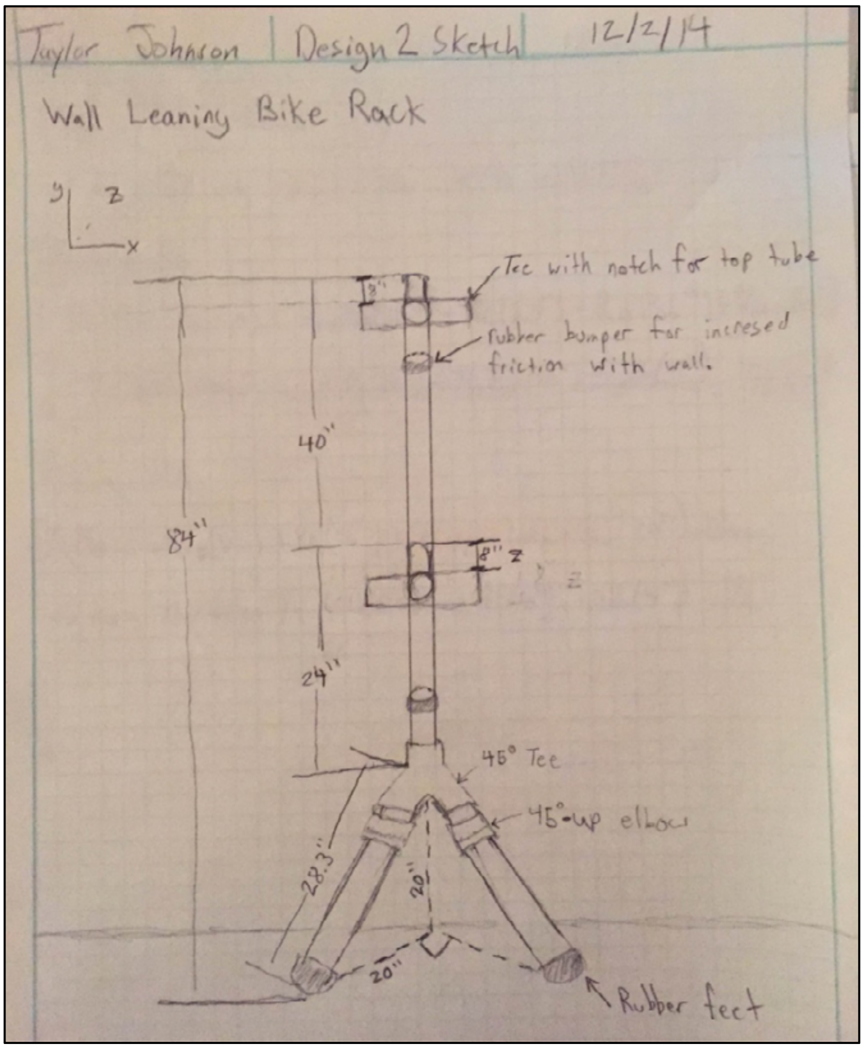

Figure 2: Sketch

Figure 3: 3-D Rendering

Figure 3: 3-D Rendering

Benchmark

There are a variety of solutions to this problem currently on the market. Many bike racks use simple hooks and wall mounts to hold the bikes. Figure 4 shows an elegant solution made of steel pipe. The skills and equipment needed to produce such a work of metal are not available. Instead the rack will be equally stable but made out of ABS pipes and fittings that can be found at the local Home Depot.

Figure 4: Benchmark Bike Rack

Success of Project

The project will be considered a success if the device can hold two bikes and be safe to operate. The device must not tip while in use in order to be considered safe.

Description of Analysis

For the device to be a success pre-construction analysis is needed. There are endless aspects to any project that could take hours to analyze. The primary (critical) analyses take priority to the secondary. The critical elements in this project are as follows: Static stability of the rack under load (will it tip?). Deflection of the main pipe under load (will it bend?). Sufficient friction at the feet of the rack (will it slip?). Failure due to overload at the mounts (will it break?). These analyses will determine the driving dimensions of the rack. If the rack deflects too much or breaks too easily, a stronger (in this case larger diameter) pipe will be needed. If the device is not stable or will not produce enough normal force for the friction to keep it from sliding, a new design must be employed.

Scope of Testing

Once the device has been constructed there will be a round of testing. The tests will correspond to the function statements and the analysis stated above. The device will be tested for tipping stability, friction slip on smooth floors and deflection under load. The extent of the overload test will be limited because the device will not be pushed to failure. If the device was tested to failure there would be nothing to present at the end of the project.

ANALYSIS

Dimensions

To determine the dimensions of the bike rack a road bike was inspected and measured (figure 1). A width of 19in between the supports was considered because the top tube dimension of the bike was 21in. The width had to be reduced because a ladies road bike was measured to only have 19in length of top tube. The calculation then became simple (appendix A3-1). Accounting for the diameter of the ABS pipe a 16in width was derived for the supports center to center. This dimension will make the rack more universal than the previous value of 19in. The 16in dimension does not need to be exact but rather the analysis suggested a range of 17in-15in for the width dimension.

The height was determined by taking the tallest measurement of the road bike (figure 1) and doubling it then adding 4in of clearance for the bike handler (total 84in). The depth was determined by taking the width measurement of the road bike and adding 2in of clearance. This will allow for the user to mount the bike easily and perform chain maintenance while the bike is mounted. With a depth of 20in the use can spin the cranks to easily clean/lube the bike chain or adjust shifters. With these dimensions in place the rack, with bikes mounted should take up 52ft^3 and save 18ft^3 of space in the hallway.

Deflection

To optimize the weight, size and cost of the bike rack deflection at the load was analyzed. Refer to appendix A-1 for examples of the calculations used for the analysis. To ensure safety for the user and check one component of stability the Deflection formula: **Def=ML^2/2EI** was used

to check if the support members would deflect significantly under load. For this formula an online recourse was used to find the Modulus of Elasticity **$E=340x10^3$ psi** for ABS plastic (www.makeitfrom.com). The I value was derived for the size of pipe used.
For round pipe **$I= pi(D^4+d^4)/64=3.036in^4$**.

This calculation is especially useful for optimizing weight as well as cost of the materials. The values of the *D* and *d* can be swapped for smaller less expensive pipe values and very quickly test if they will deflect under load (Figure 5). It turned out that with a 3" pipe there would only be **$6.78x10^{-5}$in** of deflection. This is below the required value for deflection so the 3" pipe is rigid enough for this application. Finally the deflection equation was run through excel (figure 5) and added the values for the various common diameters of ABS pipe. This showed that even the 1.5in OD pipe satisfies the deflection requirement. The 1.5in pipe only deflects **$6.73x10^{-4}$in** making it an option in terms of the horizontal load member deflection. This calculation has shown that the smaller, lighter and more affordable pipe size can be used at the load supports. To try to maintain a safety factor of 2.0, two inch pipe will be used in the horizontal supports**.**

Pipe Size	Outer D	Inner D	Thickness factor	I factor(in^4)	Deflection(in)
3in	3.507in	3.075in	61.858	3.036	**6.7804E-05**
2in	2.375in	2.072in	13.385	0.657	**3.13E-04**
1.5in	1.900in	1.615in	6.229	0.306	**6.73E-04**

Figure 5: Deflection at Load Supports (Excel)

The displacement of the vertical pipe under 30lb loads was found using displacement and slope at the loads. This method accounts for the instantaneous displacement at each load. It also considers the slope of the displacement as the top load is placed above the bottom load and combines them for a comprehensive analysis of the vertical member displacement. The lower load displacement came out to be 0.15 in and the upper load displacement 1.07in. Tighter there should be about 1.22in of displacement at the top with two 30lb loads. See appendix A4-5 for specific calculations.

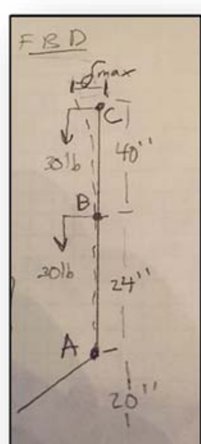

Figure 6: Deflection of Vertical Pipe

Free Standing Statics

The analysis was conducted with the following assumptions: The fittings and joints are treated as continuous pipe, and bikes weight 20lb each. Refer to Appendix A4-1—>A4-3 for specific calculations.

To analyze the statics of the device the weights of the components were found using 3in pipe at 1lb/ft. Appendix A4-1 illustrates this process. With the forces acting through the centroids of their given shapes and the orientation of the bike loads the resultant forces were found (appendix A4-2). The reaction force at the feet of the rack was found to be N=71.7lb. With this data, the sum of the moments formula was used to find the reactions on the vertical member at A and B to be 16.1lb. The rack will not tip if the force of friction at the feet can overcome the reaction forces off the wall (2 x 16.1lb). The coefficient of friction (μ) for rubber is 0.50 to 0.85 according to the engineering handbook. The calculation for friction force (μN) resulted in a force of 50.2lbf which is greater than the wall reaction force of 2 x 16.1= 32.2lb.

Evolution of Analysis

The first design that underwent analysis turned out to be impractical for the desired outcomes. This work and the associated green sheets are being included to document the evolution of the project. Please see Appendix A2-1 through A2-6 for calculations on the original design.

To analyze overall stability of the original design the weights of the various components were found with 3in pipe weighing 1lb/ft. Next the sum of the moments was used about point B to find one of the unknown reaction forces in the feet (R_A). Then the forces were summed in the Y direction to find the other reaction force in the feet (R_B). Again the moments about B were summed but this time to find the center of gravity in the X direction (X_{CG}). With these calculations done the moments were summed about A and B respectively to find the tipping force that the rack could resist when the reaction force in the feet reached zero. The initial rack dimensions showed poor results only resisting a 6lb force at the top (Appendix A2-1). On the second attempt the design was able to resist a 13lb tipping force front to back but only 8.9lb back to front (appendix A2-2). A relationship was found in the calculations: if the length of the feet is increased (plus or minus X_{CG} depending on the direction the force is applied) the force that can be resisted at the top increases.

Thus far the analysis was demanding some changes be made to meet the requirement of 14lb tipping force. The 12in front and 12in rear feet were not going to work. As seen in appendix A2-3 the length of the foot in front was increased to 17in and the length behind the rack was increased to 15in. This yielded positive results with a 17lb force (front) and 13.7lb force (back) but still not quite on the mark. On the next attempt the dimensions were changed to 18in front foot length and 13in rear foot length. This turned out just right with the rack resisting 15.1lb tipping force front and 14.6lb tipping force rear.

It was not until calculating the tipping force when applied to the side of the rack that serious issues arose. The original design can only resist 7.7lb when applied to the rack from the side (appendix A2-6). This is a serious issue because the width of the rack would have to double for it to pass the 14lb requirement. Increasing the width would totally change the design of the rack and it would no longer pass the space saving and easy to assemble requirements. This calculation has ultimately lead to the scrapping of the design altogether. Instead of a free standing bike rack the device will be one that can brace itself against a wall. A wall leaning rack can more thoroughly satisfy the stability, rigidity and space saving requirements which are the main motivations driving this project. The rack was redesigned and analyzed as seen above.

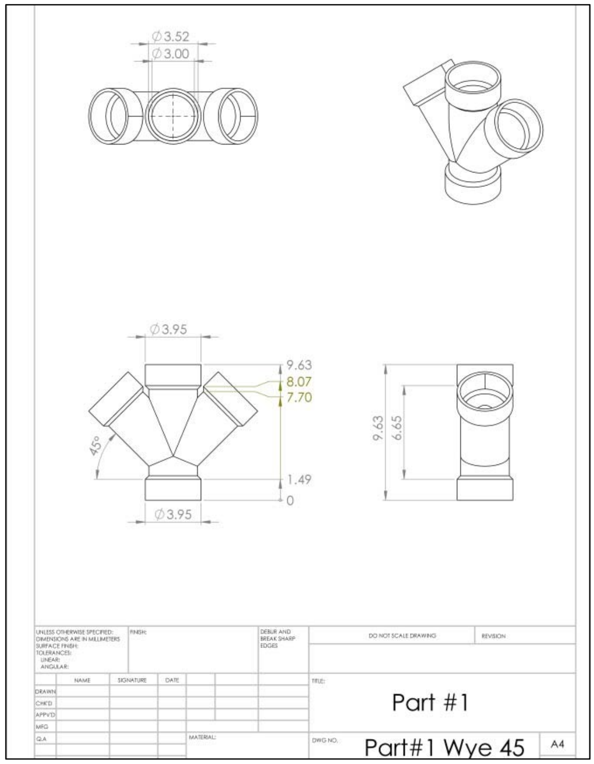

Figure 10: Part#1 3” Double San Wye 45.

Part Drawings & Solidworks

Solidworks was used to experiment with different orientations of pipe lengths and fittings for dimensional analysis. The Muller Industries website provided models of all of the pipe fittings that they offer. The straight sections of pipe were generated as needed. The vertical pipe and leg dimensions were determined by the size of the bikes and did not change much. Instead, this platform was excellent for trying out ideas for load bearing arms. Like the design in figure 3, many iterations were virtually assembled and analyzed. These ideas were measured in Solidworks to see if they would accommodate the bike dimensions and retain a compact design. The process was repeated until the optimal design presented itself. Drawings were made from the part models that were to be used in the final design. See appendix B2 for the complete set of drawings.

This part of the design process took longer than expected. The projected Solidworks hours were 5 hours and the actual time spent in Solidworks was closer to 10 hours. Although it took a great deal of time, Solidworks modeling was highly beneficial to the project. This program saved hundreds of hours that could have gone into constructing prototypes only to see them fail. Thanks to Solidworks the final design was highly functional and only in need of a few clearance corrections to be perfectly executed.

METHODs & CONSTRUCTION

Figure 7: The 10ft pipe stock had to be cut to length. A saw, guide, clamps and table were used.

Method

The construction of the bike rack will be completed in multiple steps. The construction will be relatively simple due to the nature of ABS pipes and fittings. The pipe will be cut to the various lengths. These lengths will have to fit the dimensions of the drawings while compensating for the radius of the pipe itself. Nothing will be glued together until all of the proper lengths of pipe have been cut.

After the lengths have been cut the cut ends must be de-burred and cleaned. Next there must be a dry fit assembly of the rack. The pipes will be gently put into the tees and elbows in the proper configuration to check if things are lining up properly. Any major errors will be noticeable during this phase. The rack must be measured carefully after the dry fit. Any mistakes are to be fixed before the final assembly with pipe glue. After the final assembly the glue must be allowed to dry for 30 minutes.

Tools

- Pipe saw
- Measuring tape
- Cutting table
- Clamps
- Saw guide
- File
- Sand paper
- Screw Gun
- ¼” Drill bit
- Gloves and eye protection

Figure 8: The cut parts had to be sanded and cleaned before gluing.

Construction Procedure

The 10’ long 2” and 3” diameter pipe stock was laid on a long bench and placed in a saw guide to achieve strait cuts. The desired length was measured (twice) and marked with a scoring pen. Quick grip clamps were applied to the work piece and a pipe saw was used to make the cut. The cut piece was re-measured to be sure it fit within tolerance. This process was repeated for all 14 cut pieces. After cutting the parts were de-burred and cleaned with alcohol.

The 14 pieces cut and 15 fittings (figure 8) where assembled for a dry fitting. The rack dimensions of interest were measured on the dry fit. The rack satisfied the dimensions on the first fit. With the dry fit still in place, holes were drilled through the tees, wye and legs. Lag bolts with wing nuts were installed in the holes to insure the rack could be broken down for storage and transport. Next the dry fit assembly was taken apart (except for the bolted sections). For the gluing, eye protection and gloves were used.

The glue was applied in a well-ventilated area and the position of the glued fittings was carefully controlled. Using the hash marks on the fittings, the proper angles were made for the legs and support arms. The support arm assemblies were glued and left to dry for 30min before the rest of the rack was glued. Figure 10 shows the completed, glued and bolted rack. The construction took a total of 7 hours over two days.

Figure 9: Finished Rack
The completed rack came out to be within the desired dimensions.

Parts List

Description	Part #	Quantity
3” Double San Wye 45	1	1
3” x 3” Coupler	2	2
3” x 17.5” Lower Vertical Pipe	3	1
3” x 33.5” Upper Vertical Pipe	4	1
3” x 2” Double San Wye 90 Reducing	5	2
3” x 3” Elbow 45	6	2
3” x 17” Leg	7	2
3” End Cap	8	2
2” Elbow 90	9	8
2” x 2” Coupler	10	4
2” x 4.5” Support Arm	11	4
Bolt ¼ x 5”	12	7
Wing Nut	13	7

Manufacturing Issues

Great care was taken when making the pipe cuts. With measure twice cut once practices there were no pipes that had to be re-cut. The 10ft long pipe stock was challenging to handle in a small garage but the tables and clamps were sufficient. The saw guide did not make perfectly strait cuts because it was much shorter than the 3" pipe diameter. Some of the cuts turned out crooked but the lengths fell within the tolerances allowed. There was an issue drilling the holes because the pipe diameter is too great for a standard drill bit. Therefore an extra-long drill bit was acquired to drill the holes. Overall, manufacturing went more smoothly than anticipated. With careful planning, the construction of the rack was completed without any major issues or defects.

Drawing Tree

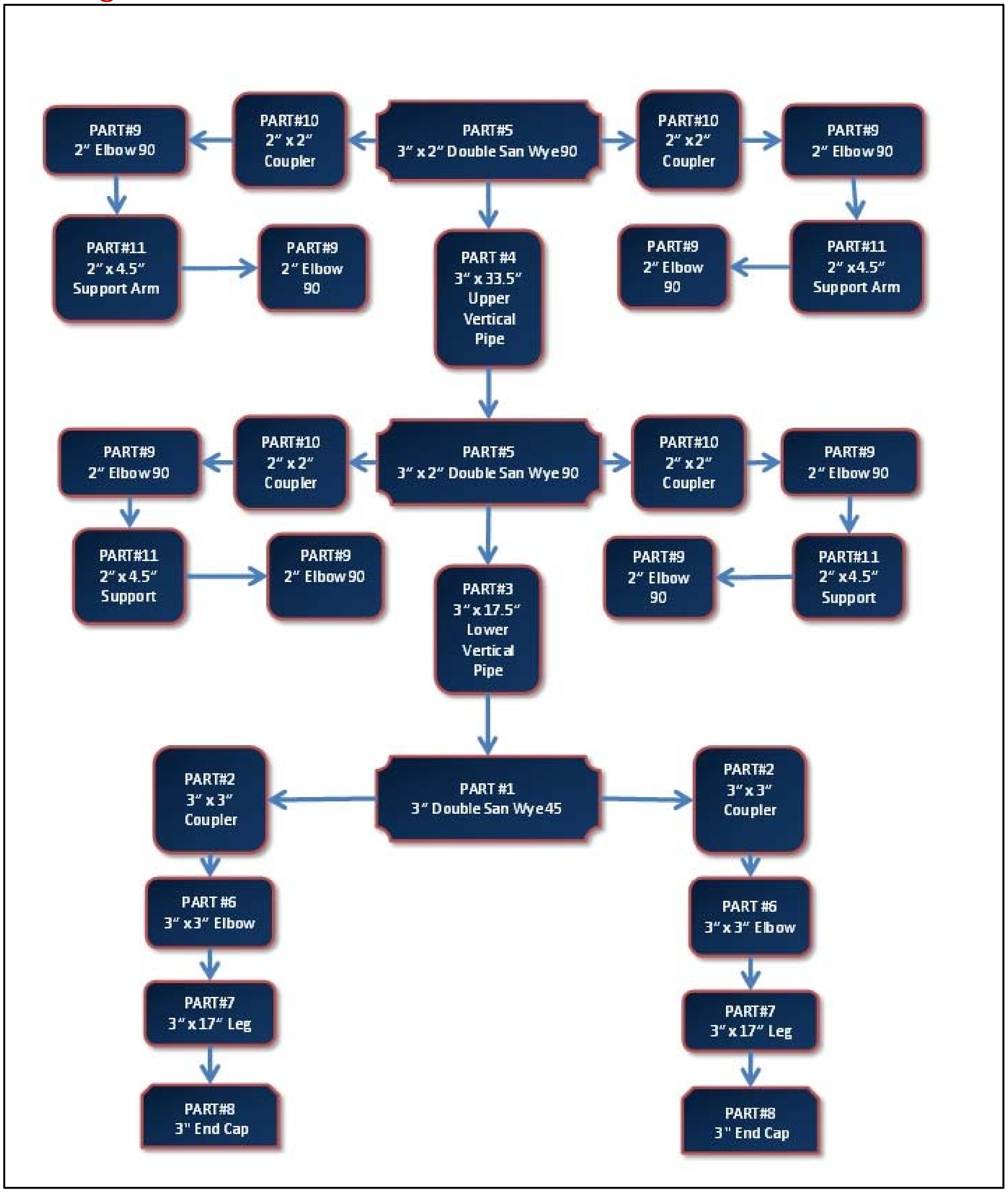

Figure 6: Drawing Tree

TESTING METHOD

Introduction

The rack will be tested to see if it meets the following requirements:

- Loaded rack volume must not exceed V = 52 ft^3 (+/- 4 ft^3).
- Must occupy no more than 10ft^2 (+/- 0.5 ft^2) of floor area.
- Must support two instances of: A 40lb load, placed on two horizontal supports. This load is placed at 42" high and again at 84" high (+/- 0.5"). The load points down, perpendicular to the support members
- Must meet a safety factor of 2.0
- Must not deflect more than 0.25" (+/- .05") at the vertical member, under bike load.
- Must support 2 bikes.
- Rack legs must not slip under load.

Most of the testing concludes in pass or fail results. The length, width and height will be measured to determine volume occupied by loaded rack. One test will determine if the rack can support two road bikes. Another test will determine if the rack will slip on smooth concrete under load. The final test will determine the deflection in the vertical member when loaded with 80lbs of weight. It is predicted that the bike rack will satisfy all of the stated requirements. All measurements will be taken with a measuring tape and recorded by hand. The testing tasks 5a-5h are estimated to be completed in about 17 hours (appendix E1).

Method

Test 1: The rack was placed flush against a wall and two road bikes were placed on the rack. The rack was left with the bikes loaded for two days. The deflection from the wall of the rack was measured.

Test 2: The rack was placed on a smooth concrete floor and placed flush against a wall. The rack was then loaded with two road bikes to see if the legs would slip out on a smooth floor.

Test 3: The rack was loaded with two sets of 30lb weights on ropes at the top and bottom load bearing horizontal members. This test was designed to check my pre-construction deflection analysis. The deflection was measured with a tape measure in the middle of the top of the rack. (Figure 12).

Test 4: The rack was placed flush against a wall and loaded with 40lb weights on ropes at the top and bottom load bearing horizontal members. This was an overload test to see if the rack conformed to the safety factor of 2.0. The typical road bike weight is 20lbs.

Lastly, the floor area occupied by the device measured 12ft^2 less than the original configuration of bikes in the hallway. Please refer to Appendix-**F** for the full testing report.

Results

Description	Outcome
Test1: Bike Holding	Success, the rack held the bicycles and did not deflect at all.
Test2: Friction/Slip	Success, even without the rubber, the legs of the rack did not slip.
Test3: Deflection	Success, the rack deflected 1.22-1.25in as predicted in the analysis phase.
Test4: Overload, K=2.0	Success, the rack did not fail.

←Figure 12: Deflection Test Deflection measured under two 30lb loads.

Figure 13: Rack with→ Bikes Zero deflection under bike load.

BUDGET & PROJECT MANAGEMENT

Budget

The current budget (see appendix D1) shows estimated costs for the parts it will take to construct the bike rack. The actual cost verses estimated cost is shown. The cost of the rack was greatly increased by the use of 3” pipe fittings. These large fittings are very uncommon and therefore very expensive. The projected total cost of $50 in parts was far below the actual cost. The double san 45 degree wye cost $45 alone. The cost of this device could be greatly reduced with production connections. If the parts were ordered from the manufacturer rather than a retailer and ordered in big lots rather than individual parts, it could cut the cost by nearly fifty percent.

Gantt chart

The Gantt chart in Appendix E (E1) shows the tasks needed to complete the project. It is important to have a Gantt chart in order to conceptualize which tasks are going to take more time and deserve more focus. This tool is important for staying on task and completing a project on time. As tasks are finished, the time they took is recorded so that the next stage of the project can be planned more accurately. Some of the tasks took less time than estimated. For example task a1 (brainstorming) took one hour instead of the estimated two. On the other hand task 1f (Drawings) took ten hours instead of five. More time will be allocated to the drawing task on the next project.

Fall quarter is dedicated to the proposal and drawing phase of the project. In winter the rack will be constructed and tested. In the spring the final report and presentation are to be completed. Each of these assignments comes with its own challenges that don’t always present themselves right away. Therefore, like many parts of this project, the Gantt chart was updated as the project matured.

Design Evolution

The design evolved over the course of the project. The free standing attribute was omitted to keep the design compact. The design went from a two post rack to a single post rack with angled legs. The analysis evolution drove the design evolution. When the original design was determined to be unstable, a new design was produced. The Solidworks assembly assessment also greatly influenced the design. This platform allowed for many designs to be evaluated without being built. Solidworks was a quick way to try an arrangement and measure whether or not it would grant the needed clearances. Cost also drove the evolution of the design. The final change to the design was to replaces the 3” tees with reducing (2”) 90 degree wyes. This allowed for the use of 2” pipe and elbows for the load bearing assemblies. The 2” pipe was significantly less expensive especially where the fittings were concerned. Since the design called for eight 90 degree elbows, reducing them to 2” saved about $40.00. The evolution of the analysis and design produced a much more efficient and compact solution to the problem of storing two road bikes than any of the initial concepts were.

DISCUSSION/CONLCUSION

Discussion

The goal of this project was to produce a device to solve the problem of a hallway crowded with bicycles. The engineering method was to be applied to this problem. In the fall the functions and requirements were defined and analysis was carefully conducted. Revisions to the analysis and design were necessary to optimize the device. In winter a device was carefully constructed. In the spring the device was tested to see if it met the requirements and functions from fall.

Initially it was difficult to spend long hours on a design only to find it was not sufficient and have to start over. It was frustrating to go through but this was the first attempt at an engineering project from concept to building and testing. By the time the spring testing was over, it was clear the hard work had paid off. The device performed the functions perfectly and passed all of the tests (overload, deflection, holds two bikes). Also, the device saved 12ft^2 of floor area in the entry way.

In the end the project was over budget by about $125and over schedule by 20 hours. The estimated budget of $50 was too low off due to the massive changes to the design by the end of the design phase. The project timeline was off schedule after the first design and analysis having to be scrapped and started over. From winter quarter on the project remained on schedule.

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2. The Engineering Toolbox, n.d., from http://www.engineeringtoolbox.com/ABS-drainage-pipe-d_1732.html

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APPENDIX A-Analysis and Calculations

A-1 Deflection

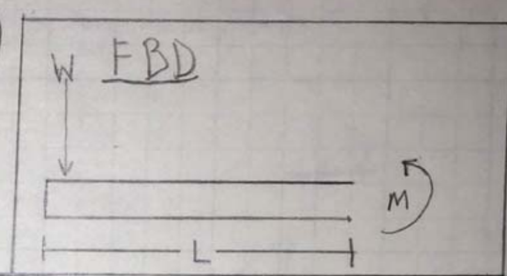
Taylor Johnson   Support Deflection   10/20/2014

Given: $W = 30\,lbs$, $L = 20\,in$ $E_{ABS} = 340\times10^{3}\,psi$
$D = 3.507\,in$ $d = 3.075\,in$

Find: Find moment M + Max Deflection

Soln: $M = WL$ $I_p = \frac{\pi(D^4 - d^4)}{64}$

$D_{ef} = \frac{ML^2}{2EI}$



$M = 30\,lbs\,(20\,in)\left(\frac{1\,ft}{12\,in}\right) = \boxed{50\,lb\cdot ft}\left(\frac{.007\,psi}{1\,lb\cdot ft}\right) = \boxed{0.35\,psi}$

$I_p = \frac{\pi(3.507\,in^4 - 3.075\,in^4)}{64} = \boxed{3.036\,in^4}$

$Def. = \frac{0.35\,psi\,(20\,in)^2}{2(340\times10^3\,psi)(3.036\,in^4)} = \boxed{6.78\times10^{-5}\,in}$ acceptable deflection

A2-1Tipping Load

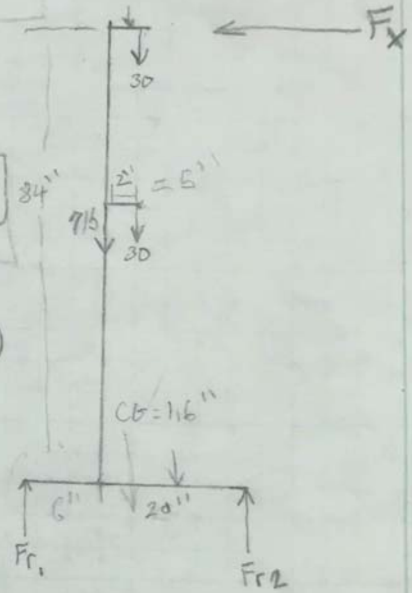
Taylor Johnson | Tipping Analysis | 11/15/14 1/2

$\Sigma M_{Fr_2} = F_{r_1}(26'') - [20''(7\,7 + 1.3\,lb) + 30(18'')(2) + 4(0.15lb)(19)]$

$= F_{r_1} = \frac{306 + 1080 + 11.4}{26} = \boxed{53.7\,lb}$

$\Sigma F_y = 53.7lb + F_{r2} - 2(7) - 30(2) - 1.3lb$
$- 4(0.15lb)$

$\Rightarrow F_{r2} = 75.9 - 53.7lb = \boxed{22.2lb}$



Finding CG

$\Sigma M_{Fr2} = 0 = F_{r1}(26'') - \frac{M_{tot}}{2}(20'' - X_{cg})$

$X_{cg} = \frac{\frac{53.7}{2}(26)}{(\frac{75.9}{2})} - 20'' = \boxed{1.6''}$

Tipping Force

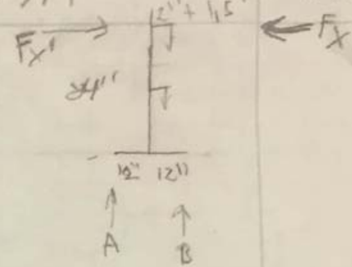
$\Sigma M_{Fr_1} = 0 = \frac{mg_{tot}}{2}(X_{cg} + 6'') - F_x(84'') + 26(F_{r2} @ 0) = 0$

$F_x = \frac{(\frac{75.9}{2})(7.6'')\,2}{84} = \boxed{6\,lb}$

$X_{cg} = \frac{F_{r1}(26'')}{mg_t} \quad \frac{26 - F_{r1}(26'')}{mg_t} = 7.6''$

A2-2 Tipping Load

Taylor Johnson | Tipping Analysis | 11/15/14 2/2



$\Sigma M_B = -2(30)(15.5in) - 7(2)(12in) - 1.3(12in) - 4(0.15lb)(15.5in) + F_{rA}(24)$

$= F_{rA} = \dfrac{930 + 168 + 15.6 + 9.3}{24} = \underline{46.8\,lb}$

$\Sigma F_y = 46.8lb + F_{rB} - (2\cdot 30lb) - 2(7) - 1.3 - 4(0.15) - 2lb$

$= F_{rB} = \underline{31.1\,lb}$ $\quad \underline{mG_t = 77.9lb}$

CG

$\Sigma M_B = 0 = F_{rA}(24'') - mGT(12'' - X_{CG})$

$\underline{X_{CG}} = \left(\dfrac{F_{rA}(24)}{mGT}\right) - 12'' = \underline{2.4''}$

Tipping

$\Sigma M_A = mG_t(X_{CG} + 12'') - F_x(84'')$

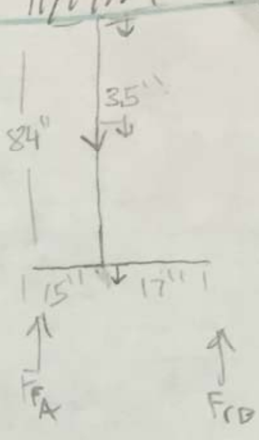
$\Rightarrow F_x = \dfrac{77.9lb\,(14.4'')}{84''} = \boxed{13.4\,lb}$

$\Sigma M_B = mGT(12 - X_{CG}) - F_x'(84)$

$F_x' = \dfrac{77.9\,(9.6'')}{84''} = \underline{8.9\,lb}$

A2-3Tipping Load

Taylor Johnson | assume mg(Hooks) = negligable | 11/19/14



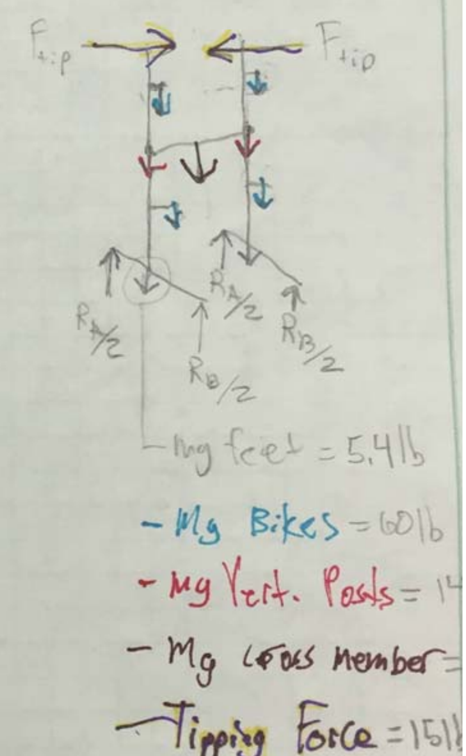
$$\circlearrowleft + \sum M_B = -F_A(32") + 2(7lb)(17in) + 2(30lb)(13.5in) + (1.3lb)(17in) + (5.4lb)(16in)$$

$$\Rightarrow \underline{F_A} = \frac{1156.5\,lb\cdot in}{32\,in} = \boxed{36.1\,lb}$$

$$\sum F_y = 36.1lb + F_{rB} - (2)(30lb) - (2)(7lb) - (1.3lb) - (2)(2.7lb)$$

$$\Rightarrow \underline{F_{rB}} = 80.7lb - 36.1lb = \boxed{44.6lb}$$

CG assembly



$$\sum M_B = F_{rA}(32") - mgT(17" - X_{cG})$$

$$\Rightarrow \underline{X_{cG}} = \frac{36.1lb(32") - 17"(80.7lb)}{(80.7lb)} = \boxed{2.7"}$$

Tipping (Front to Back)

$$\circlearrowleft + \sum M_A = mgT(X_{cg} + 15") - F_x(84")$$

$$\Rightarrow F_x = \frac{80.7lb(17.7")}{84"} = \underline{17lb}$$

Tipping (Back to front)

$$\circlearrowleft + \sum M_B = mgT(17" - X_{cg}) - F_x'(84")$$

$$\Rightarrow F_x' = \frac{80.7lb(14.3")}{84"} = \underline{13.7lb}$$

Req. $F_x = \underline{14lb}$ 13" + 18"

A2-4Tipping Load

Taylor Johnson | Tipping Analysis | 11/20/14 | 1/3

<u>Given</u> -Rack loaded with 2 (30lb) bikes, assume MG(hooks) negligible
-3" pipe @ 1lb/ft
Tipping Force Requirement $F_x = 14\,lb$

<u>Find</u>: Can the rack resist a 14 lb force applied horizontally at the top (front + back)

<u>Assume</u>: weight of hooks is negligible. Treat Tees + Elbows as continuous pipe

<u>Solution</u>

<u>Weights</u>

$MG\ feet = (2)(31")(1\,lb/ft)(1\,ft/12\,in) = \underline{5.2\,lb}$

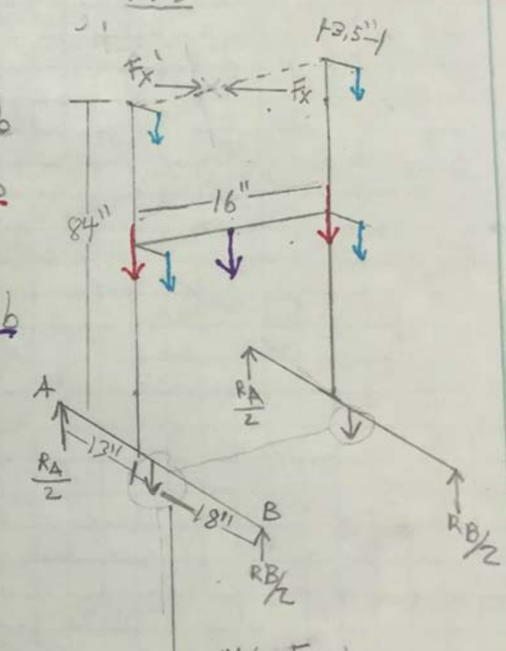
$MG\ Vert.\ Posts = 2(84")(1\,lb/ft)(1\,ft/12\,in) = \underline{14\,lb}$

$MG\ Bikes = 2(30\,lb) = \underline{60\,lb}$

$MG\ Cross\ Mem. = 16"(1\,lb/ft)(1\,ft/12\,in) = \underline{1.3\,lb}$

Force MG acts through the centroid of the pipes

FBD



MG Feet
MG Bikes
MG Verticle Posts
MG Cross Member

A2-5Tipping Load

Taylor Johnson | Tipping Analysis Cont. 11/20/14 2/3

Find $R_A + R_B$

$$\circlearrowleft^{+} \sum M_B = -R_A(31'') + 14lb(18'') + 5.2lb(3\tfrac{1}{2}'') + 1.3lb(18'') + 60lb(18''-3.5'')$$

$$\Rightarrow R_A = \frac{1226\ lb\cdot in}{31\ in} = \boxed{39.5\ lb}$$

$$\sum F_y = R_B + 39.5 - 5.2lb - 14lb - 60lb - 1.3lb = 0$$

$$\Rightarrow R_B = 80.5lb - 39.5lb = \boxed{41\ lb}$$

Find Center of Gravity of Rack + Bike Load (CG)

$$\circlearrowleft^{+} \sum M_B = R_A(31'') - mG_{total}(18'' - X_{CG}) = 0$$

$$\Rightarrow X_{CG} = \frac{39.5lb(31'') - mG_t(18'')}{mG_t}$$

$$X_{CG} = \frac{39.5lb(31'') - 80.5lb(18'')}{80.5lb} = \boxed{2.8''}$$ (from Vert. Posts toward front of rack)

Tipping (Front to Back)

$$\circlearrowleft^{+} \sum M_A = 0 = mG_t(x_{CG} + 13'') - F_x(84'')$$

$$\Rightarrow F_x = \frac{80.5lb(15.8)}{84''} = \boxed{15.1\ lb} > 14lb$$ requirement ✓

Tipping (Back to Front)

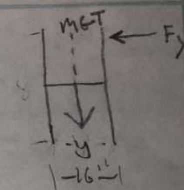
$$\circlearrowleft^{+} \sum M_B = 0 = mG_T(18'' - x_{CG}) - F_x'(84'')$$

$$\Rightarrow F_x' = \frac{80.5lb(15.2'')}{84''} = \boxed{14.6\ lb} > 14lb$$ requirement ✓

A2-6Tipping Load

Taylor Johnson | Tipping Analysis | 11/20/14 | 3/3

Tipping (Side)



$Y_{CG} = \frac{1}{2}y$ (symmetrical)

$Y_{cg} = \frac{1}{2}(16'') = 8''$

$\circlearrowleft \sum M_A = MGT(8'') - F_y(84'')$

$\Rightarrow F_y = \frac{80.5\,lb(8'')}{84''} = \boxed{7.7\ lb} < 14\,lb$ Req.

A3-1 Finding Width

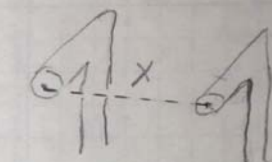
Taylor Johnson | Design Analysis | 10/20/2014

Given: ABS Plastic Pipe. Bike Top tube L = 19.5"
Pipe Size (3 in) O.D. = 3.5" W = 1 lb/ft

Find: Distance between load bearing members.

Soln: x = L − O.D.

FBD



x = 19.5" − 3.5" = 16"

$\boxed{16''}$ for clearance

A4-1 Wall Rack Statics

Taylor Johnson | Statics Calc.s | 12/2/14 1/

Given: Pipe = 1lb/ft, 2 30lb bikes, MG bumpers negligible
Treat fitting as continuous pipe.

Find: Coefficient of friction for rubber feet to resist reaction force along wall post

Soln:

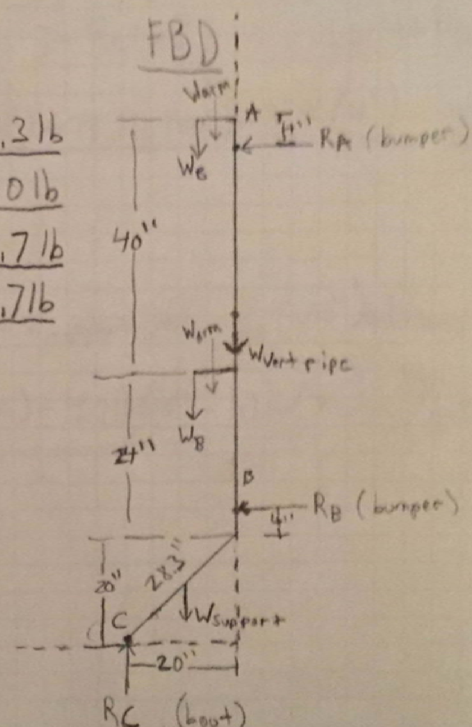
Weights

Vert. Pipe $= 64\text{in}(1\text{lb}/1\text{ft})\frac{1\text{ft}}{12\text{in}} = \underline{5.3\text{ lb}}$

Bikes $= 2(30\text{lb}) = \underline{60\text{ lb}}$

Arms $= 2(10\text{in})\left[(1\text{lb}/1\text{ft})\frac{1\text{ft}}{12\text{in}}\right] = \underline{1.7\text{ lb}}$

Support $= 2(28.3")(1\text{lb}/1\text{ft})\frac{1\text{ft}}{12\text{in}} = \underline{4.7\text{ lb}}$



A4-2 Wall Rack Statics

Taylor Johnson | Static Calcs | 12/2/14 2/

Finding R_C

$$\Sigma F_y = 0 = R_C - MG_{total}$$

$$\Rightarrow R_C = 60lb + 5.3lb + 1.7lb + 4.7lb = \boxed{71.7lb}$$

Finding R_B

$$+\circlearrowleft \Sigma M_A = 0 = W_B(8in) + W_{support}(10'') - R_C(20'') - R_B(56'') + W_{Arms}(4'')$$

$$\Rightarrow R_B = \frac{-60lb(8in) - 4.7lb(10'') + 71.7lb(20'') - 1.7lb(4'')}{56''} = \boxed{16.1lb}$$

Finding R_A

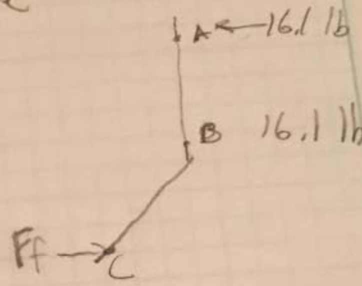
$$+\circlearrowleft \Sigma M_B = 0 = W_B(8in) + R_A(56'') + W_{support}(10'') - R_C(20'') + W_{Arms}(4'')$$

$$\Rightarrow R_A = \frac{71.7lb(20'') - 60lb(8in) - 4.7lb(10'') - 1.7lb(4'')}{56''} = \boxed{16.1lb}$$

A4-3 Friction Force

Taylor Johnson | Design 2 | 1/4/15

Friction force rubber on concrete



$\mu = 0.6 - 0.85$ (engineers handbook)

assume average $\mu = 0.7$

$F_F = \mu N$

$R_C = N = 71.7\ \text{lb}$

$F_F = 0.7(71.7\ \text{lb}) = \underline{50.19\ \text{lb}}$

$R_A + R_B = 16.1(2) = 32.2$

$F_{A+B} < F_F$ w/ rubber boots (rubber friction tape)

A4-5 Deflection in Vertical Pipe

Taylor Johnson | Deflection of Vert. Pipe 1/10/15

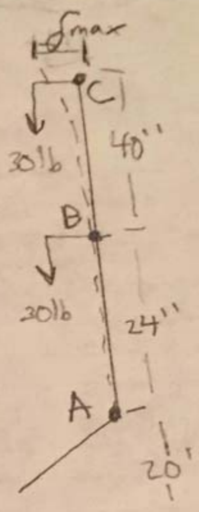
Given $I = 3.036\ in^4$

$E_{ABS} = 0.34 \times 10^6\ psi$

Find deflection in vertical pipe

Soln moment & displacement max

FBD



@B $M_B = M_C = 30lb(9\ in) = 270\ lb \cdot in$

$$\delta max = \frac{mL^2}{EI} = \frac{270\ lb \cdot in\ (24\ in)^2}{0.34\times10^6\ lb/in^2\ (3.036\ in^4)}$$

$\delta max = \boxed{0.15\ in}$

Slope of displacement

$$\theta = \frac{mL}{EI} = \frac{270\ lb\cdot in\ (24\ in)}{0.34\times10^6\ lb/in^2\ (3.036\ in^4)} = \boxed{0.006\ in/in}$$

@C $$\delta max = \frac{270\ lb\ in\ (40\ in)^2}{0.34\times10^6\ lb/in^2\ (3.036\ in^4)} = \boxed{1.07\ in}$$

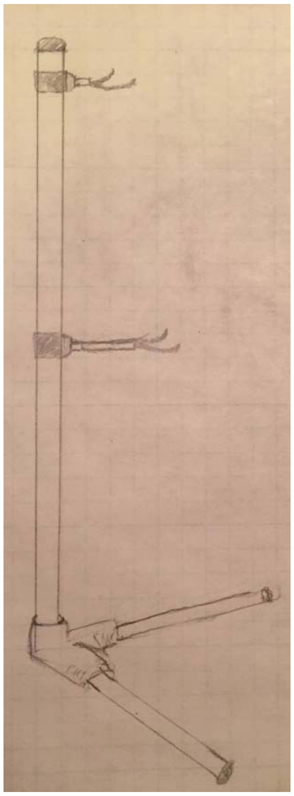
$$\theta = \frac{270\ lb\cdot in\ (40\ in)}{0.34\times10^6\ lb/in^2\ (3.036\ in^4)} = \boxed{0.0167\ in/in}$$

$\delta total = \delta_a + \delta_c = \boxed{1.22\ in}$

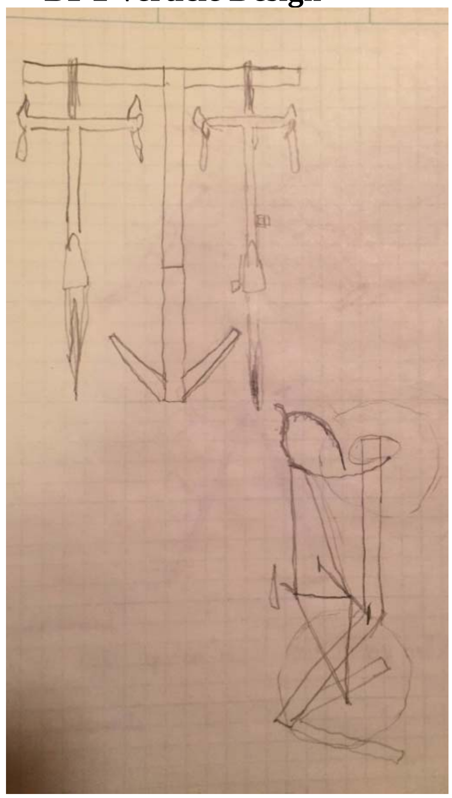
APPENDIX B - Sketches, Assembly drawings, Sub-assembly drawings, Part drawings

Preliminary Sketches

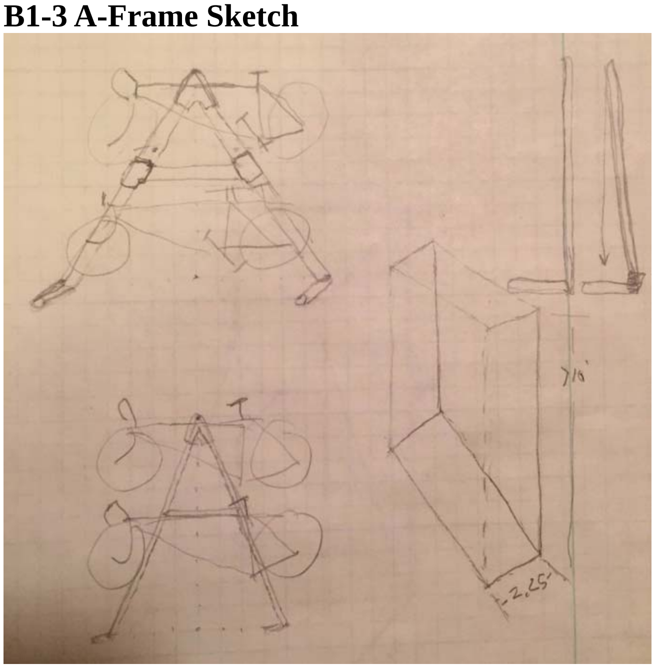
B1-1 First Sketch



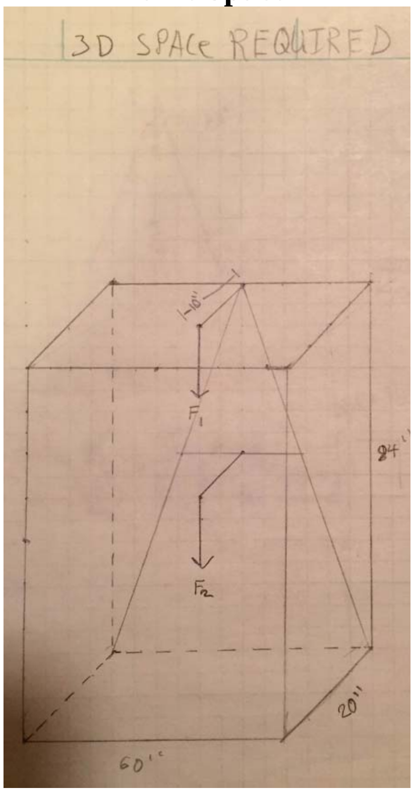
B1-2 Verticle Design



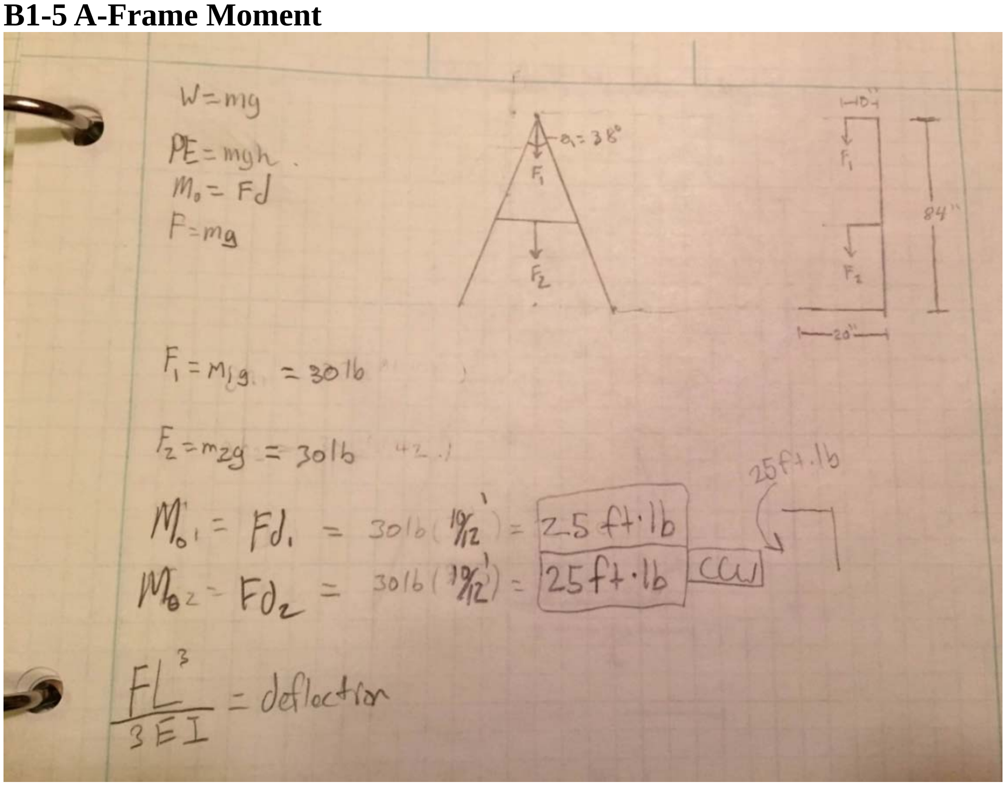
B1-3 A-Frame Sketch



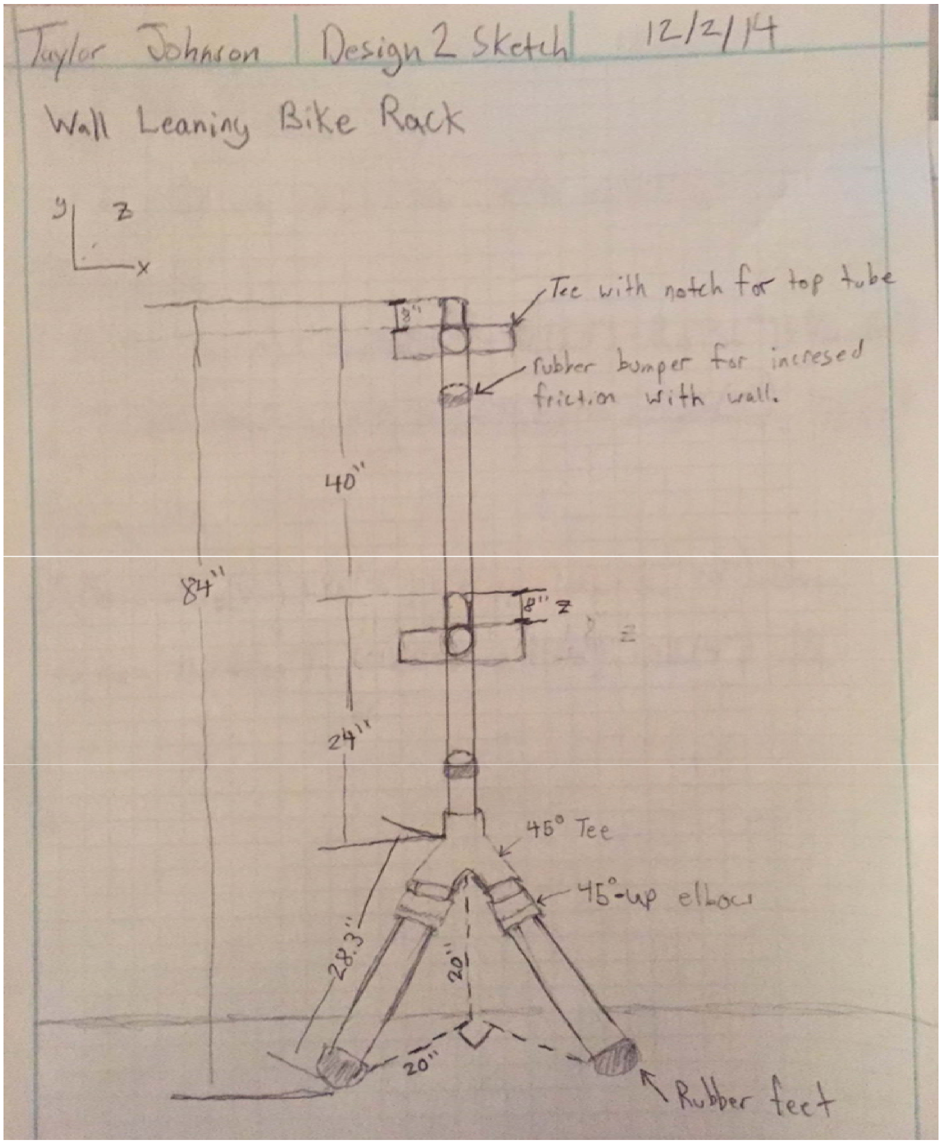
B1-4 A-Frame Space



B1-5 A-Frame Moment

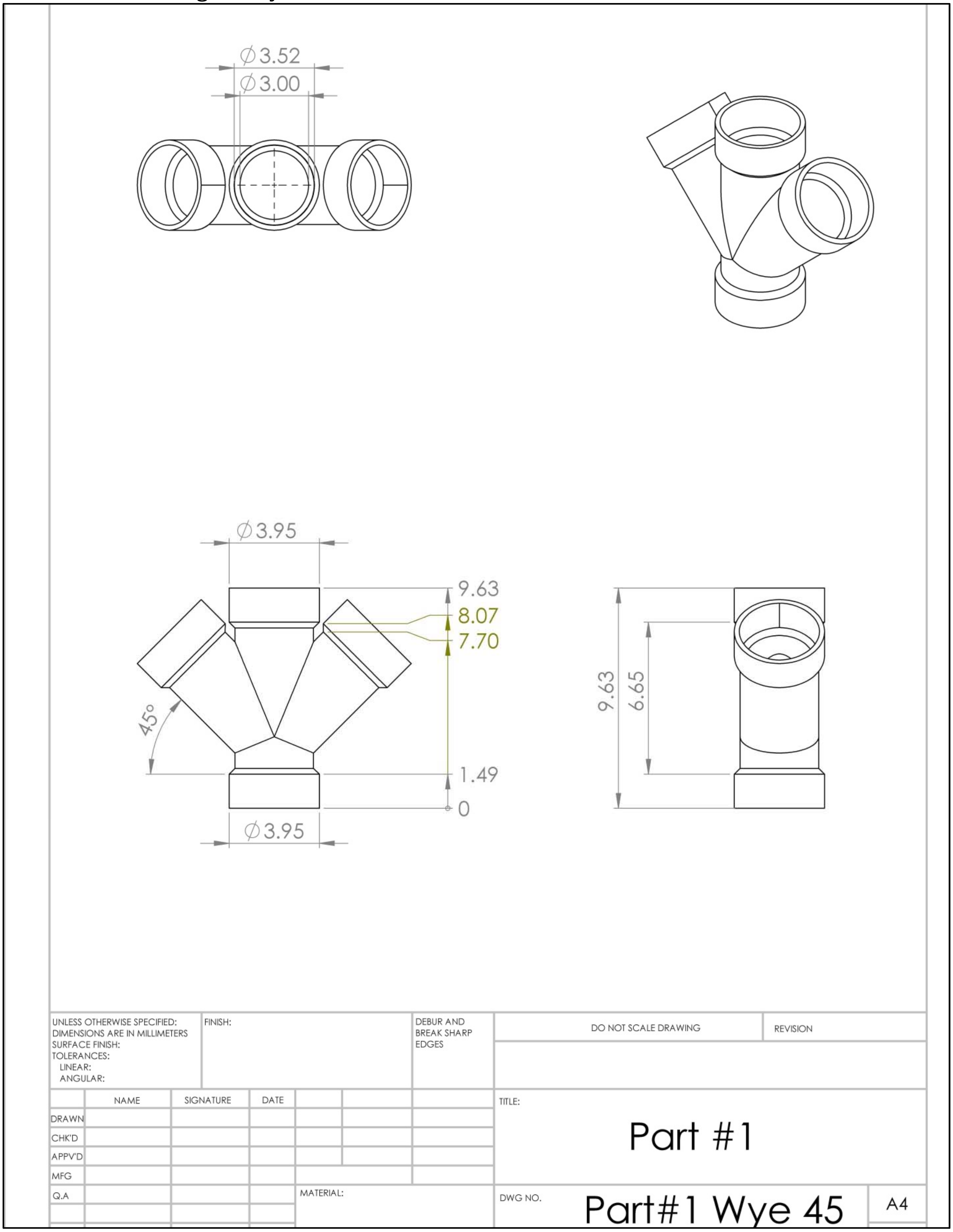


B1-6 Wall Rack Sketch

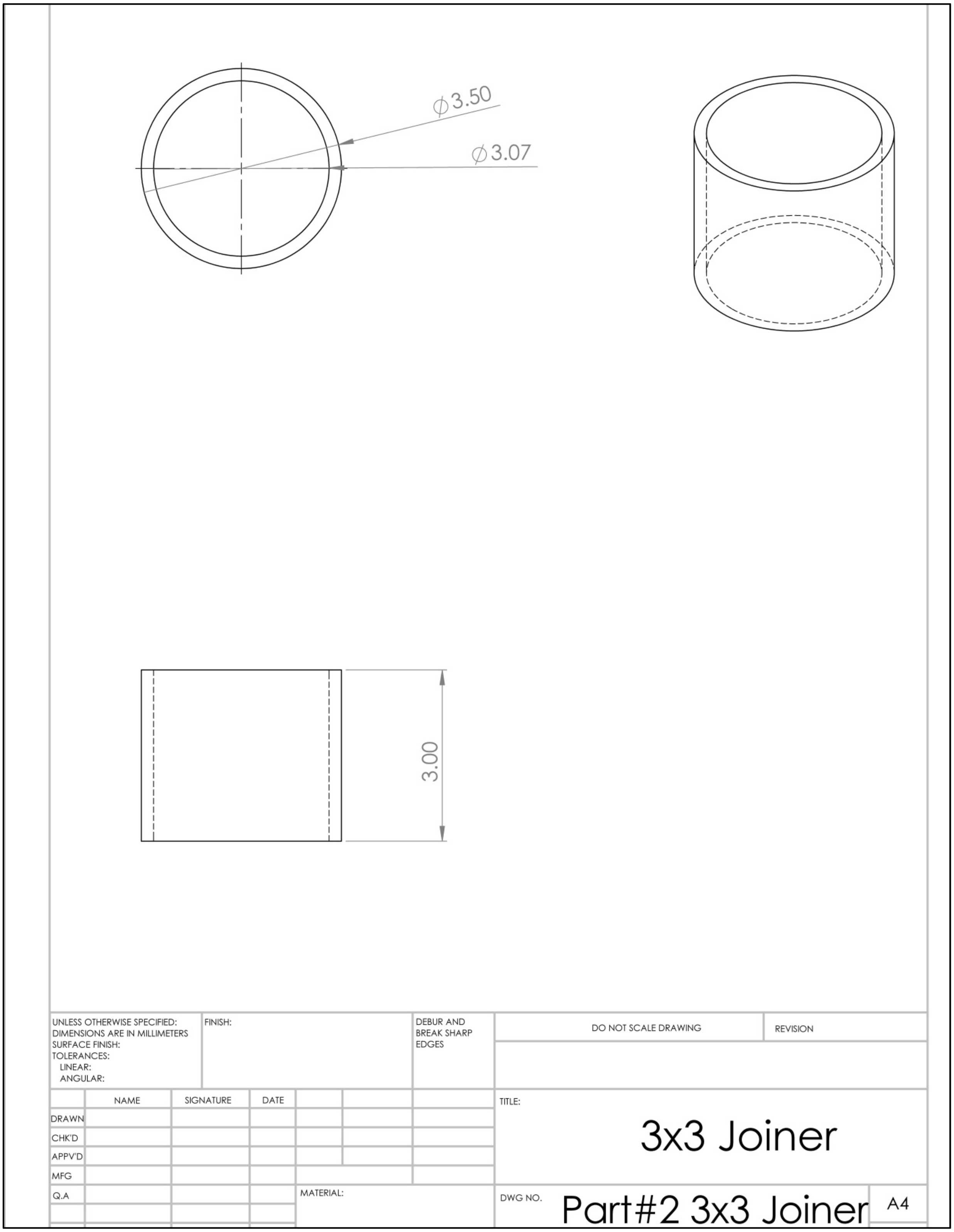


Solid Model Drawings

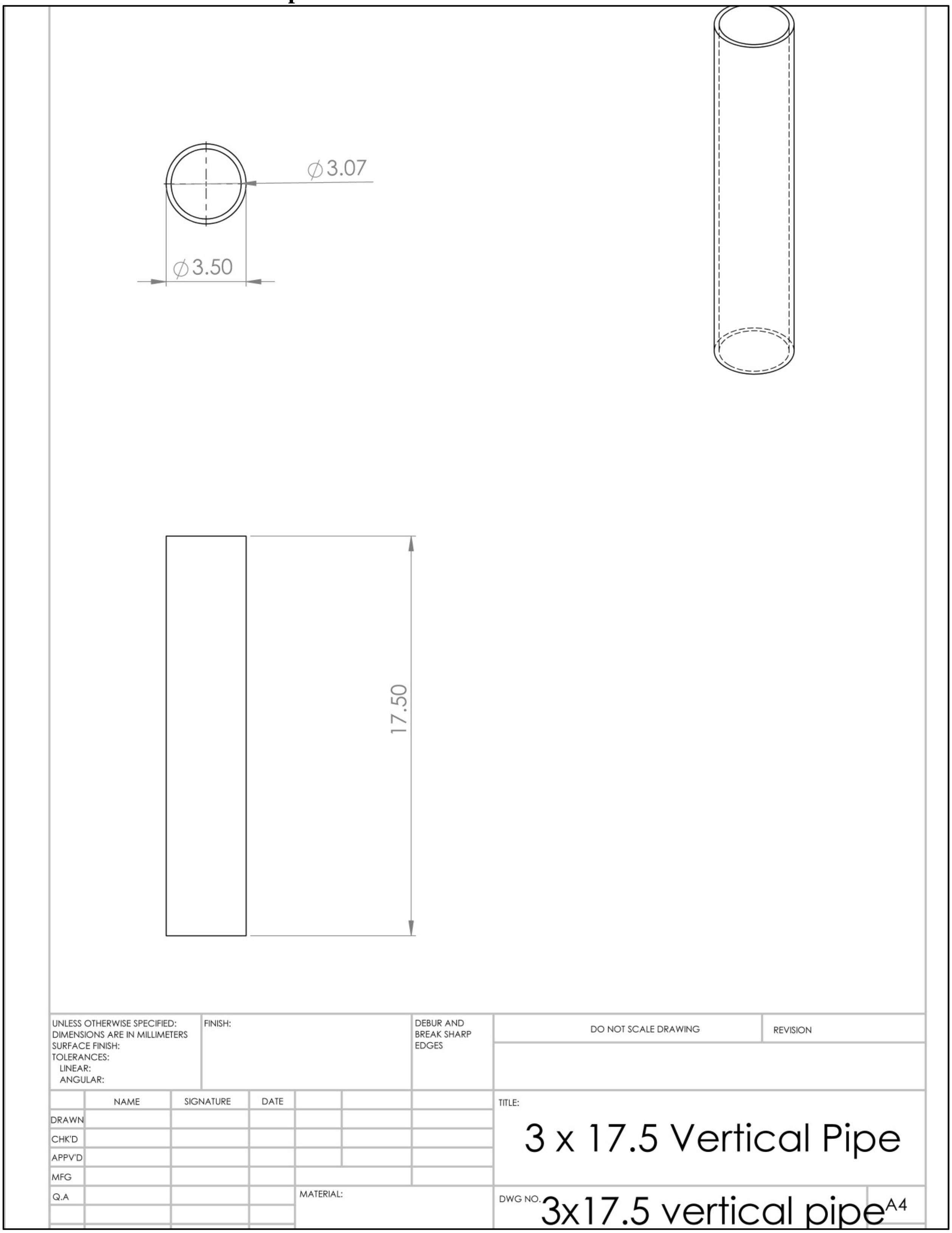
B2-1 Part #1 45 Degree Wye



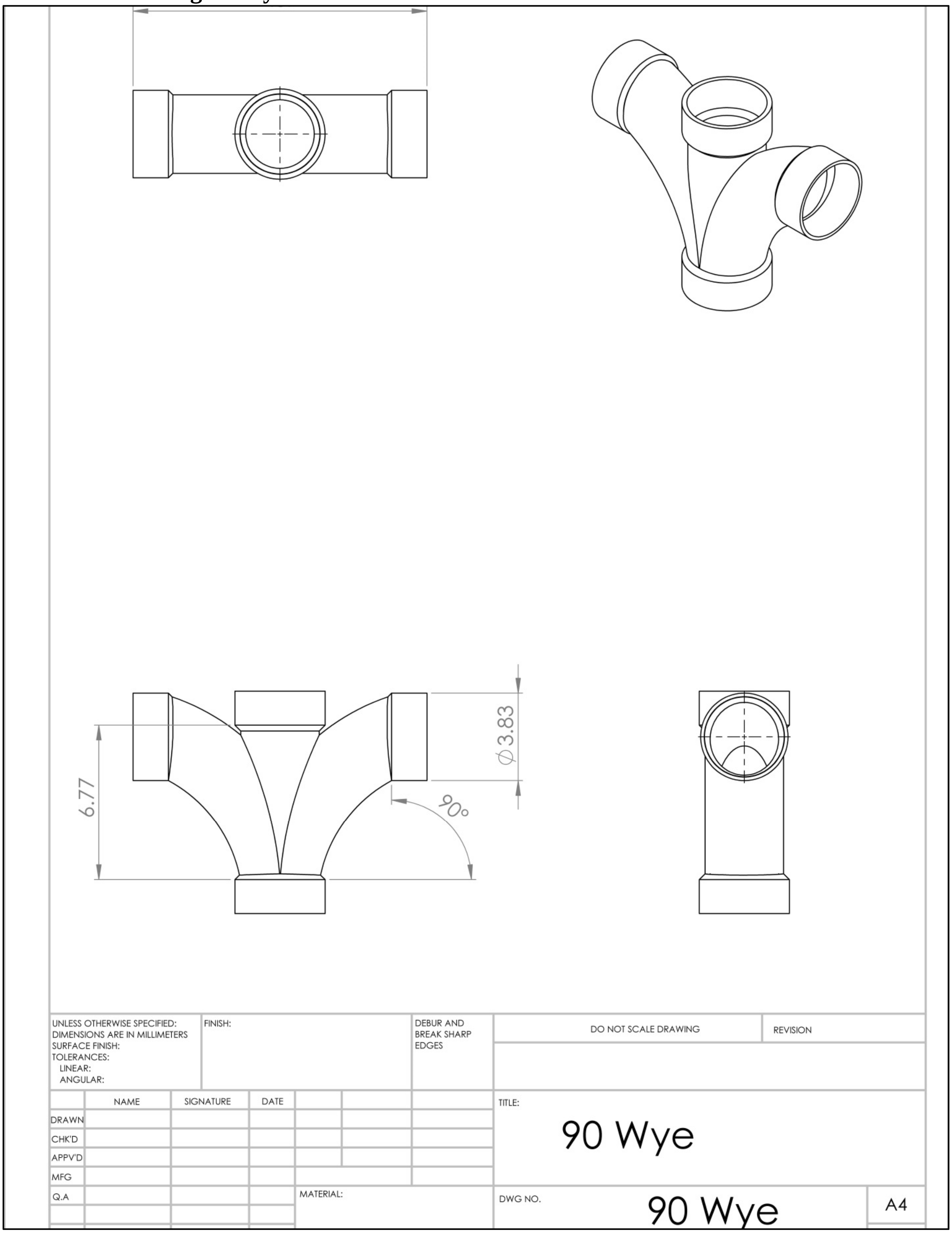
B2-2 Part #2 Joiner



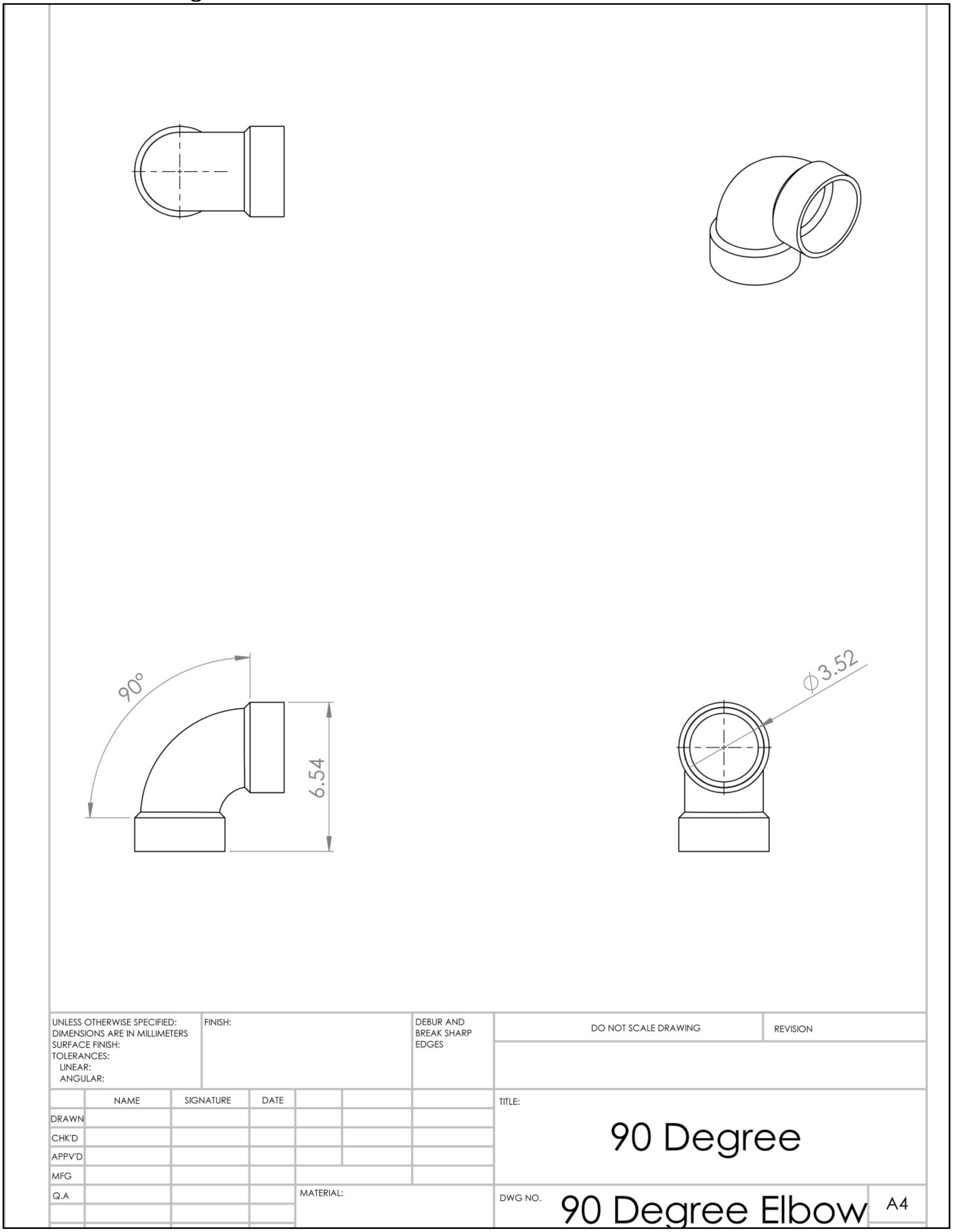
B2-3 Part#3 17.5 Vertical Pipe



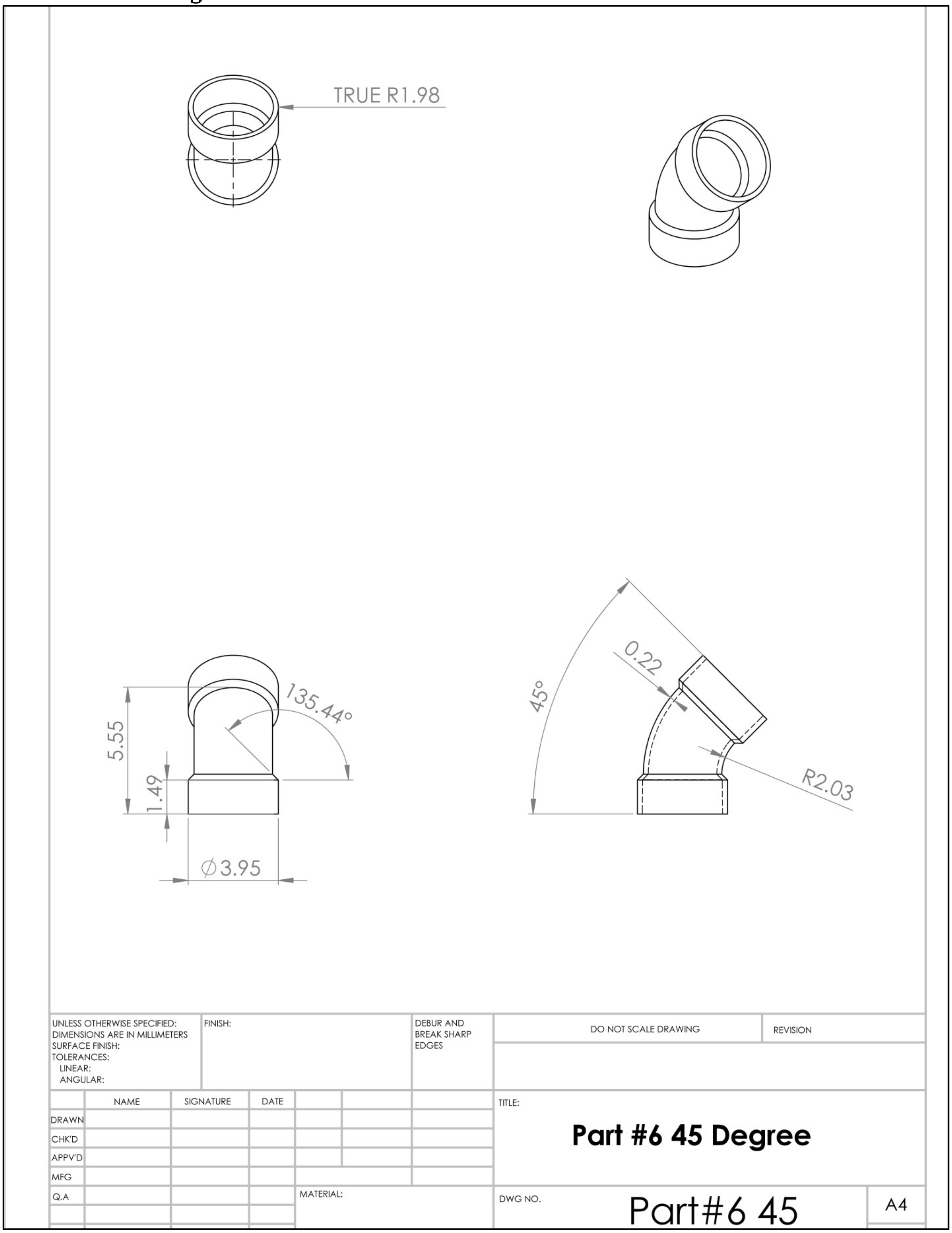
B2-4 Part#4 90 Degree Wye



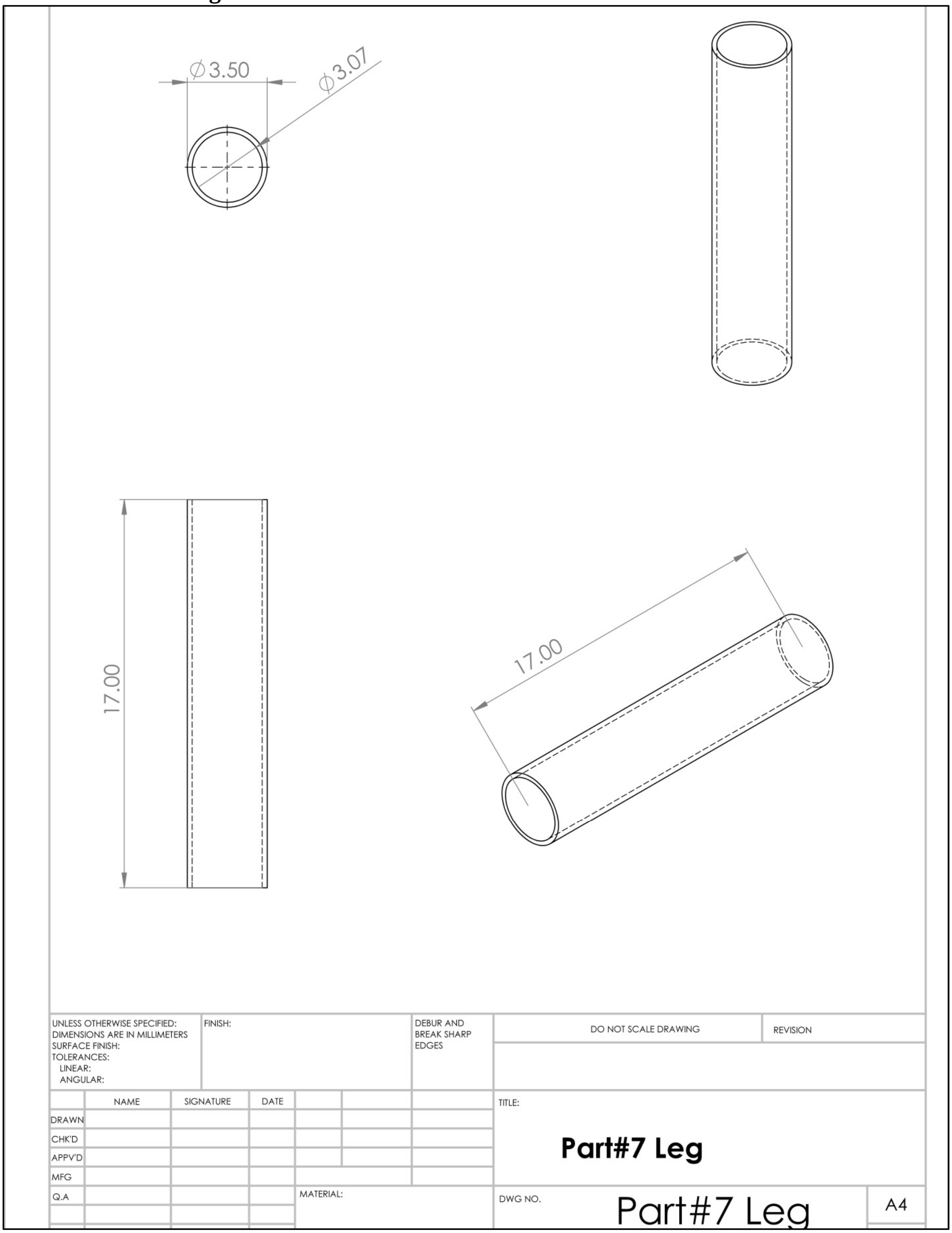
B2-5 Part#5 90 Degree Elbow



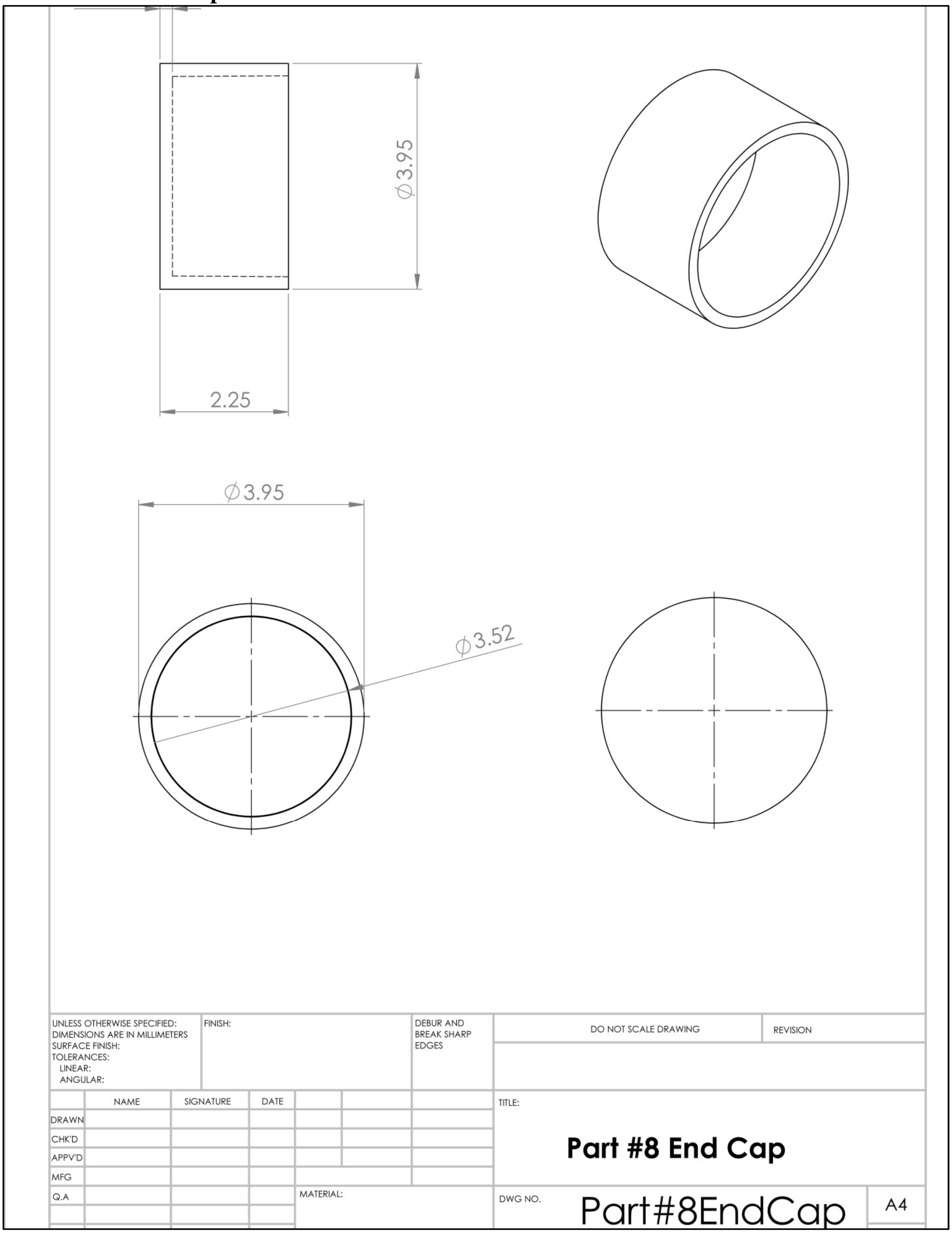
B2-6 Part#6 45 Degree Elbow



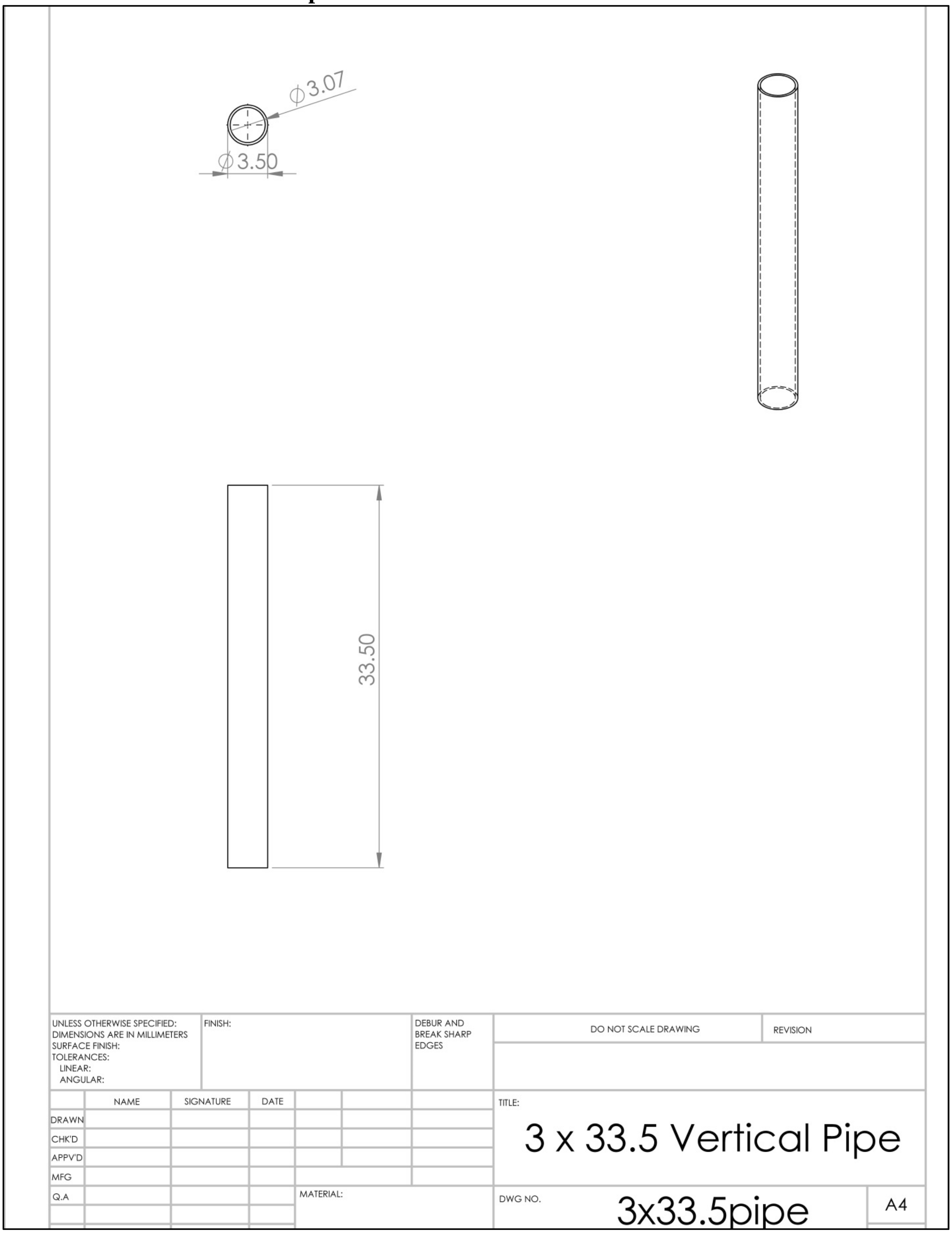
B2-7 Part#7 17in Leg



B2-8 Part#8 End Cap



B2-9 Part#9 33.5in Vertical Pipe



APPENDIX C – Parts List and Costs

C1-Parts List

Part Number	Part Description	Source	Cost
5807	2” 90 Degree (8)	Keller Supply	$25.02
5806	3” 45 Degree (2)	Keller Supply	$13.79
5817	3” Cap (2)	Keller Supply	$17.64
5835	3”x3”x2”x2” Double San Tee (2)	Keller Supply	$35.35
5889	3”x10’ ABS/DWV SCH 40 Pipe	Keller Supply	$12.71
5888	2”x10’ ABS/DWV SCH40 Pipe	Keller Supply	$6.30
13536	ABS Cement	Keller Supply	$3.29
W243	3” Double Wye	Keller Supply	$47.50
Fe2	Nuts & Bolts	ACE Hardware	$5.75
		Cost Total:	$176.48

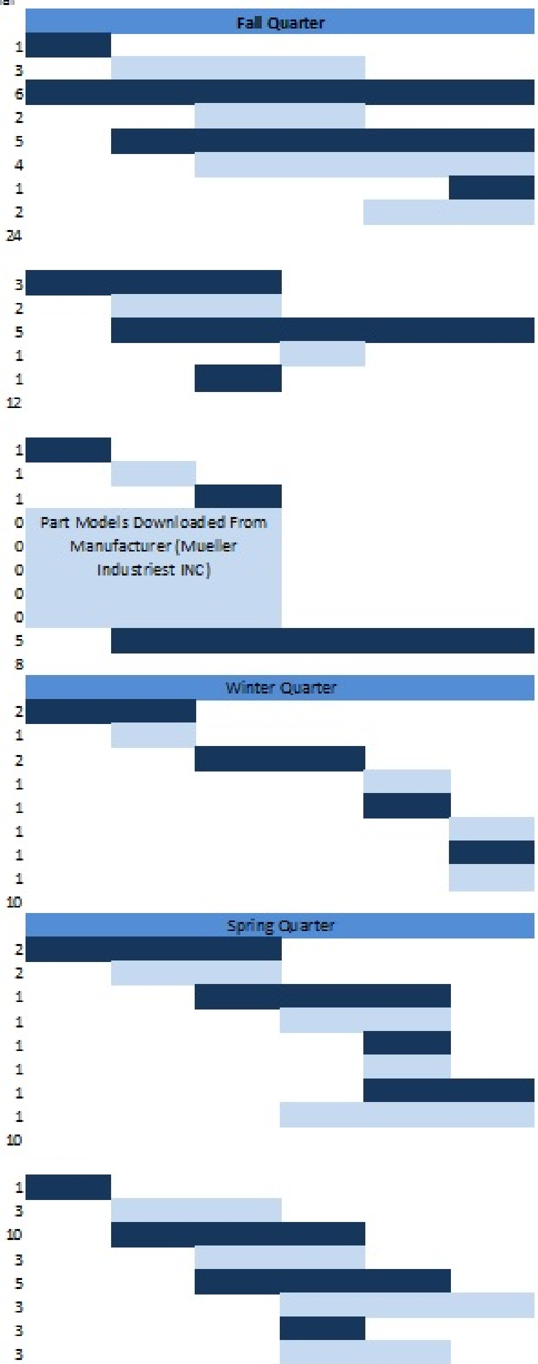
APPENDIX D – Budget

D1-Budget

Item	**Estimated Cost**
Strait Pipe	$25.00
Elbows	$15.00
Tees	$10.00
Reducer	$5.00
Pins	$3.00
Wye	$3.00
Total	$61.00
labor	$10.00
packaging	$5.00
Shipping	$20.00
Grand Total	$93.00

APPENDIX-E E-1 Gantt Chart

Task #	Description	Duration Est.	Duration Actual
1	**Proposal**		
1a	Intro	1	1
1b	Methods	2	3
1c	Analysis	6	6
1d	Parts and Budget	3	2
1e	Drawings	3	5
1f	Schedule	2	4
1g	Summary	1	1
1h	Appendix	2	2
	Total	20	24
2	**Analysis**		
2a	Statics	5	3
2b	Frictions	2	2
2c	Tipping	3	5
2d	Deflection	2	1
2e	Dimensional	1	1
	Total	13	12
3	**3D Models**		
3a	Part 1: 17in pipe	1	1
3b	Part2: 21in pipe	1	1
3c	Part3: 37in pipe	1	1
3d	Part4: 45 Wye	2	0
3e	Part5: 90	1	0
3f	Part6: 45	1	0
3g	Part7: Tee	2	0
3h	Part8: Reducer	1	0
3i	Assembly	4	5
	Total	14	8
4	**Construction**		
4a	Ordering	1	2
4b	Cut Lengths	2	1
4c	Prep ends	2	2
4d	Attatch Fittings	1	1
4e	Measure angles	1	1
4f	Drill holes	1	1
4g	Pin Joints	1	1
4h	Rubberize feet	1	1
	Total	10	10
5	**Testing**		
5a	Derive testing method	3	2
5b	Bike holding	2	2
5c	Tipping	3	1
5d	Overload	2	1
5e	Low Friction floor	1	1
5f	Organize data	1	1
5g	Analyze data	2	1
5h	Summary	3	1
	Total	17	10
6	**Final Report**		
6a	Brainstom	1	1
6b	Outline	2	3
6c	Draft	3	10
6d	Edit	2	3
6e	Create Presentation	3	5
6f	Powerpoint	3	3
6g	Update Website	1	3
6h	Final Draft	2	3
	Total	17	31
	Grand Total	91	93



APPENDIX F – Testing Report

Method

Materials needed to conduct testing:

- Two 6 foot lengths of rope
- One tape measure
- Two sets of 40lb weights
- Two road bikes
- One test site with smooth concrete floors.

Test 1: Will the rack support two road bikes? The rack was placed flush against a wall and two road bikes were places on the rack. The rack was left with the bikes loaded for two days. The deflection from the wall of the rack was measured.

Test 2: The rack was placed on a smooth concrete floor and leaded against a wall. The rack was then loaded with two road bikes to see if the legs would slip out on a smooth floor.

Test 3: The rack was leaned against a wall and loaded with 40lb weights on ropes at the top and bottom load bearing horizontal members. This was an overload test to see if the rack conformed to the safety factor of 2.0. The typical road bike weight is 20lbs. The deflection was measured with a tape measure. The distance the vertical member deflected away from the wall was recorded.

The data recorded via tape measure is accurate to 1/16 of an inch. The deflection test was repeated and recorded 10 times. The data will be graphed in excel and the average deflection will be determined. With the deflection data the elastic modulus for the rack can be derived in the post testing analysis. The amount of theoretical deflection vs. actual deflection data will be presented on a graph showing percent error. The amount of floor area saved will be presented on a graph as well.

Procedure

Test 1 was conducted 4/12/2015-4/14/2015 First the rack was placed flush against a wall in the designer's home. The lower bike was loaded followed by the upper bike with the front wheels facing opposite directions. The assembly was left for two days to determine failure. After two days the deflection of the rack from the wall was measured at the top of the rack. Loaded with two road bikes weighing 20lb each the rack exhibited zero deflection The rack passed test 1 and satisfied the requirement: *Must support 2 bikes and Must not deflect more than 0.25" (+/-.05") at the vertical member, under bike load*. Test 1 made apparent the miscalculation of certain clearances. The lower bike front wheel bumps into one of the rack legs. The upper bike front tire bumps into the lower bike seat. This makes loading and unloading the bikes slightly more clumsy and increases the risk of an accidental tip over. The clearances were off due to the design not accounting for the bike geometry when hung by its top tube. To rectify the issue a shim could be used to raise one arm of the lower support higher and another shim for the opposite arm on the upper support.

Test 2 was conducted on 4/26/2015 with the duration of 20 minutes. This time the rack was placed flush against a wall in a facility (CWU Hogue) with smooth finished concrete floors. The bikes were loaded as before; first the lower bike and then the upper bike, facing opposite directions. After the set up (5minutes) the rack was left for 15 minutes on the smooth floor. At the 10 minute mark a kick, simulating a person stubbing their toe, was applied to the bottom of the rack. Even under this fail condition the rack remained stable on the concrete floor. The bike rack passed Test 2 and satisfied the requirement: *Rack legs must not slip under load*. The rack accomplished this without the aid of rubber friction boots. The ABS caps on the legs produced enough friction force to keep the rack from slipping on the smooth test floor. During Test 2 the floor area and volume measurements were taken and recorded for later analysis.

Test 3 was conducted 5/1/2015 at CWU: Hogue for the duration of 45 minutes. Once again the rack was placed flush against the wall. Two sets of 40lb weights were threaded through the 6ft ropes. The weights were hung over the bottom horizontal support and then the top horizontal support. The distance the rack deflected from the wall was measured at the top of the rack and recorded. The rack was unloaded and reset ten times over the 45 minutes. Each deflection was recorded. The deflection data will be used to confirm the predicted elasticity of the rack. The rack passed Test 3 and satisfied the requirement: *Must support two instances of: A 40lb load, placed on two horizontal supports. This load is placed at 42" high and again at 84" high (+/- 0.5"). The load points down, perpendicular to the support members.*

Deliverables

When loaded with bikes, the rack volume is the same as the original hallway configuration ($52ft^3$) because the rack was designed to reorient the bikes without adding to the volume they take up. The footprint of the rack measured $5.12ft^2$ compared to $17.6ft^2$ in the hallway. Much of the testing was pass/fail. The rack does hold two bikes. The rack does not slip on smooth concrete. It also does not fail with two 40lb loads, passing the overload test. The deflection test while loaded with bikes was a pass as well. The rack was required to deflect 0.25in or less and it deflected 0in with bikes mounted.

APPENDIX G – Testing Data

I-1: Test Results

Description	Outcome
Test1: Bike Holding	Success, the rack held the bicycles and did not deflect at all.
Test2: Friction/Slip	Success, even without the rubber, the legs of the rack did not slip.
Test3: Deflection	Success, the rack deflected 1.22-1.25in as predicted in the analysis phase.
Test4: Overload, K=2.0	Success, the rack did not fail.

APPENDIX G – Resume

Taylor Johnson

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Qualifications:

- BSMET from Central Washington University (ABED)
- Quick learner
- Team player able to motivate and support team members
- Excellent interpersonal and verbal communication skills
- Establish, foster and develop positive relationships with clients, peers, and supervisors
- Value punctuality, neatness, and effort
- Attention to detail

Skills:

- AutoCad and Solidworks
- MasterCam
- Computer assembly
- Statics, Dynamics, Mechanical Design
- Microsoft Office

Work Experience:

Office/Landscaping/Janitorial, **Lazy F Camp and Retreat Center**, April 2009 - August 2009
Duties: Answered phones, managed camper registration, cooked for parties of 100+, cleaned bathrooms, maintained grounds

Innovations Stoves and Spa: Installer (07/08 to 10/08)
Duties: Assembling and installing wood, gas and pellet stoves. In home customer service. Threading and installing gas pipe. Delivering spas.

(07/07 to 09/07) Fred Meyer: Bakery Clerk
201 S Water St Ellensburg, WA 98926 (509) 962-0533 Manager: Dana Mathews.
Duties: Continuous food prep, customer service, operating commercial ovens, department cleaning and department closing.

(01/07 to 07/07) Haggen: Seafood Clerk
Duties: Food prep, use of sharp fillet knives, label printing, customer service, department cleaning (meat and seafood), new employee training, food demonstrations, inventory, department opening, department closing and stock ordering.

(08/06 to 11/06) Best Buy: Camera Sales Representative
Duties: Covering for other departments (i.e. computers), department closing, exceptional customer service and sales.

Education:
Central Washington University, B.A. 2015
Mechanical Engineering Manufacturing Specialization

Professional References:

Dave Burfind, Manager
Lazy H Ranch
+ Address here
(509) 962-2780

Jerry Thramer
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Jane Orleman, Artist
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